Do Occupants in a Building exhibit patterns in Energy Consumption? Analyzing Clusters in Energy Social Games

Hari Prasanna Das
Ph.D. Scholar
Department of EECS, UC Berkeley

Joint work with

Hari Prasanna Das
EECS, UC Berkeley

Ioannis C. Konstantakopoulos
EECS, UC Berkeley

Aummul B. Manasawala
IEOR, UC Berkeley

Tanya Veeravalli
EECS, UC Berkeley

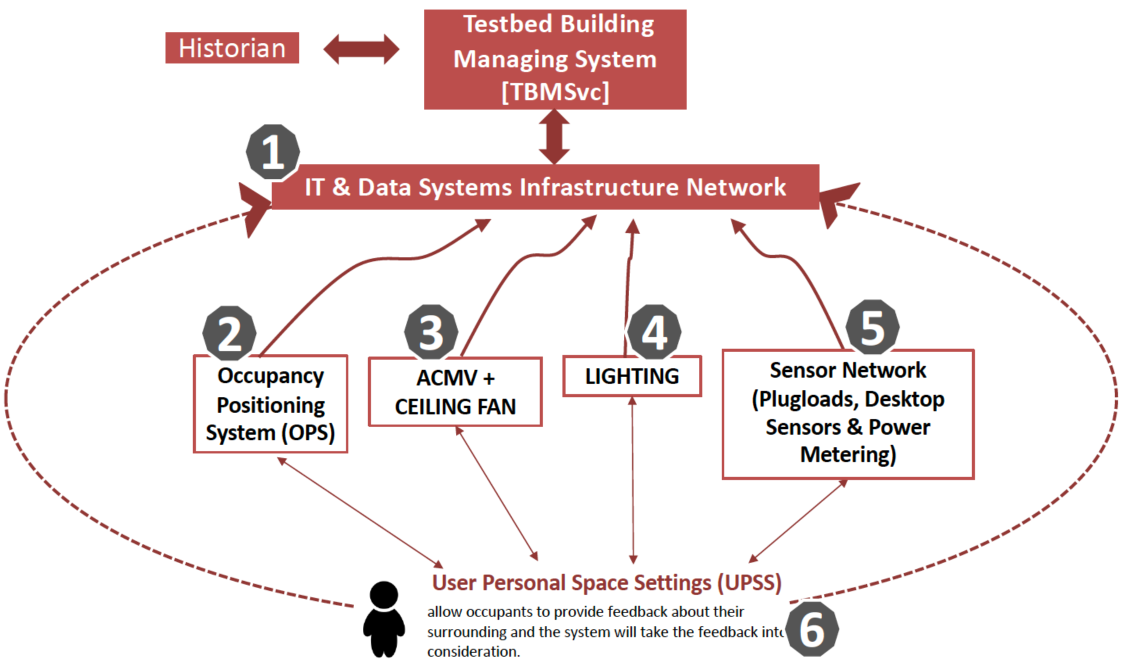
Huihan Liu
EECS, UC Berkeley

Costas J. Spanos
EECS, UC Berkeley

The Smart Building Paradigm

- Energy Consumption of buildings, both residential and commercial, account for approximately 40% of all energy usage in the U.S.
- Achieving energy efficiency in buildings is crucial
- Methods for achieving energy efficiency:

Making **building infrastructure** smart and energy efficient



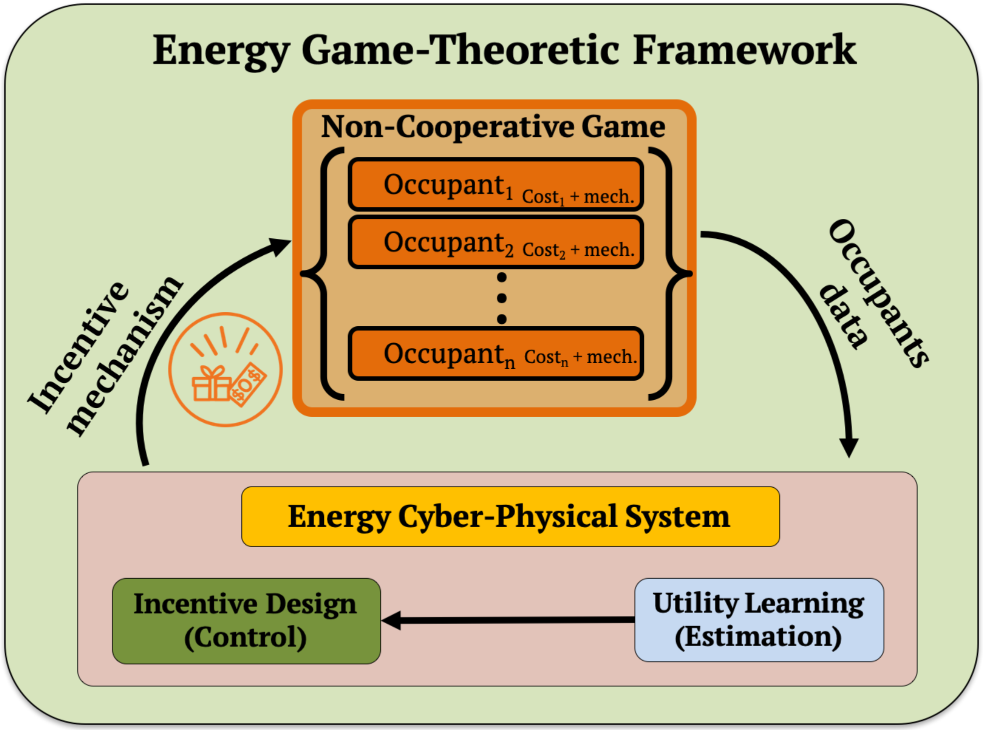
Making **occupants** energy efficient

Energy Game-Theoretic Frameworks

Source: Singapore Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) www.sinberbest.berkeley.edu

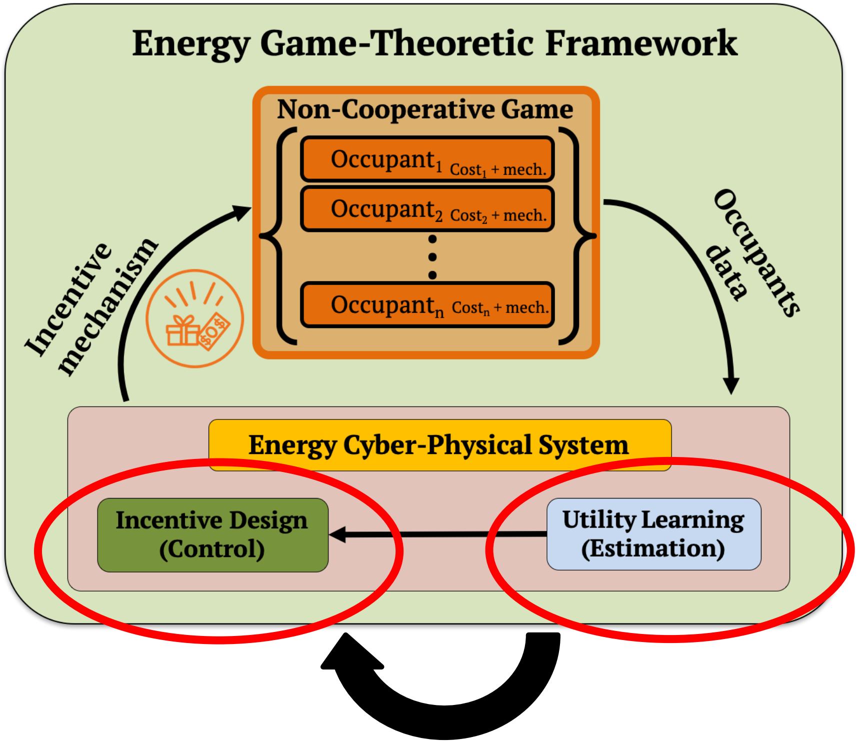
Energy Game-Theoretic Framework

Incentivize occupants to modify their behavior in a competitive game setting so that the over-all energy consumption in the building is reduced.



Utility learning is hard

To efficiently decide incentive for each occupant/player in the game, we need to know their utility function (preference towards energy usage)



Individual Utility learning is hard

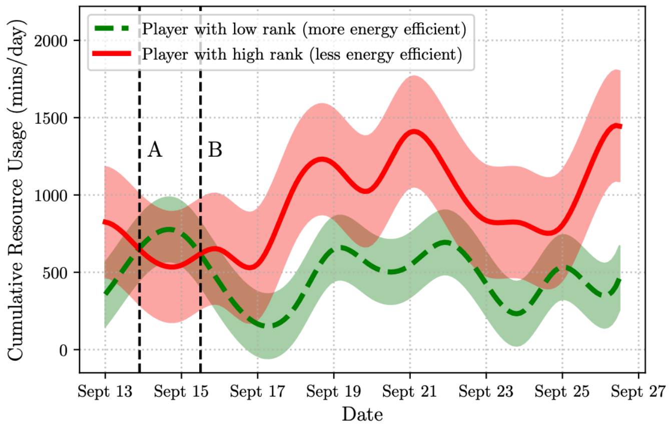
- Number of players is high
- Quality data for each player unavailable
- Human behavior resulting in utility function has high variance

Our Proposal: Segment the energy usage behavior of players into finite clusters. Under the assumption that players in a cluster will behave synchronously.

Supervised vs. Unsupervised Segmentation

Supervised Segmentation

- Requires a supervision signal: we use rank of player
- Segments players as a whole into different classes Undesirable



- Provides labels of the classes as high/medium/low energy efficient Desirable

Unsupervised Segmentation

- No supervision required
- Segments energy usage behaviors into different clusters Desirable
- No information about labelling of clusters Undesirable

Our Approach: A hybrid segmentation method

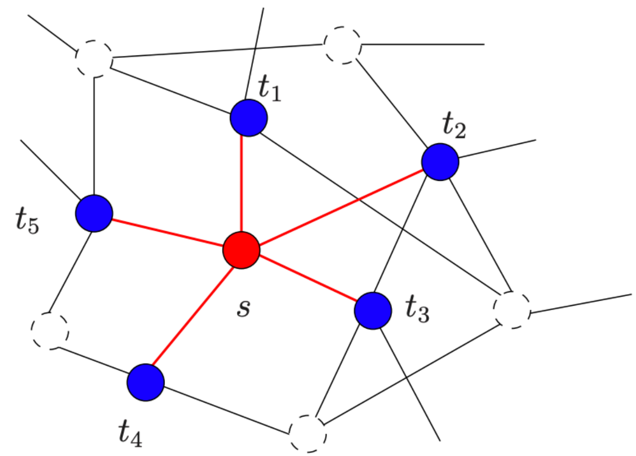
Tool for proposed segmentation: Graphical Lasso

- Graphical Lasso is a sparse penalized maximum likelihood estimator
- Features (Y) are associated with the vertex set $V = \{1,2,\dots,S\}$ of some underlying graph.
- The structure of the graph is utilized to derive inferences about the relationship between the features.
- For undirected graphical models, node for Ys is conditionally independent of nodes not directly connected to it given $Y_{V\backslash s}$. So the predictor for Ys is written as,

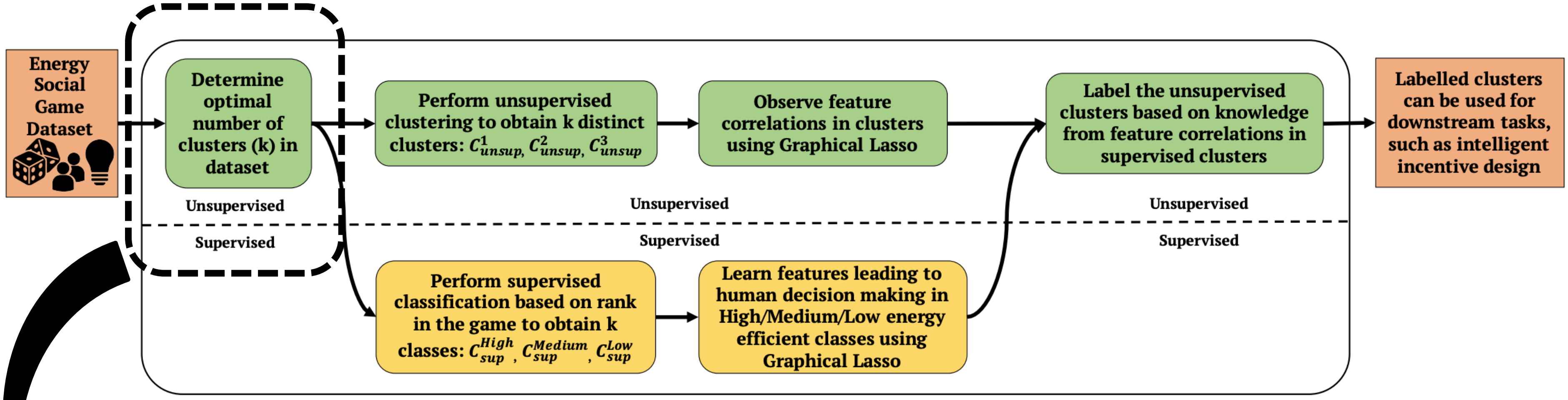
$$Y_s = Y_{V\backslash s}^T.\beta^s + W_{V\backslash s}$$

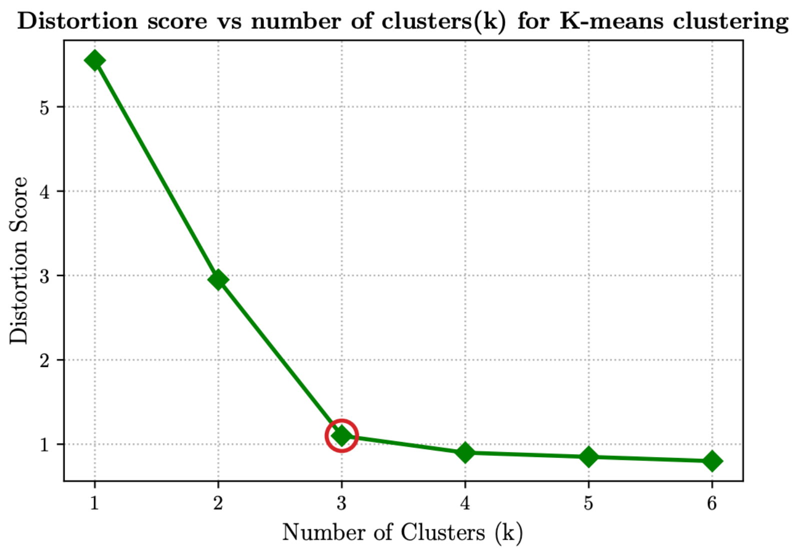
- The β^s terms dictate the edge set for node s in the graph. Obtain β^s, by solving the lasso problem

$$\hat{\beta}^s \in \underset{\beta^s \in \mathbb{R}^{S-1}}{\operatorname{argmin}} \left\{ \frac{1}{2N} \sum_{j=1}^{N} (y_{js} - y_{j,V\backslash s}^T \beta^s)^2 + \lambda \|\beta^s\|_1 \right\}$$



Proposed Segmentation Method





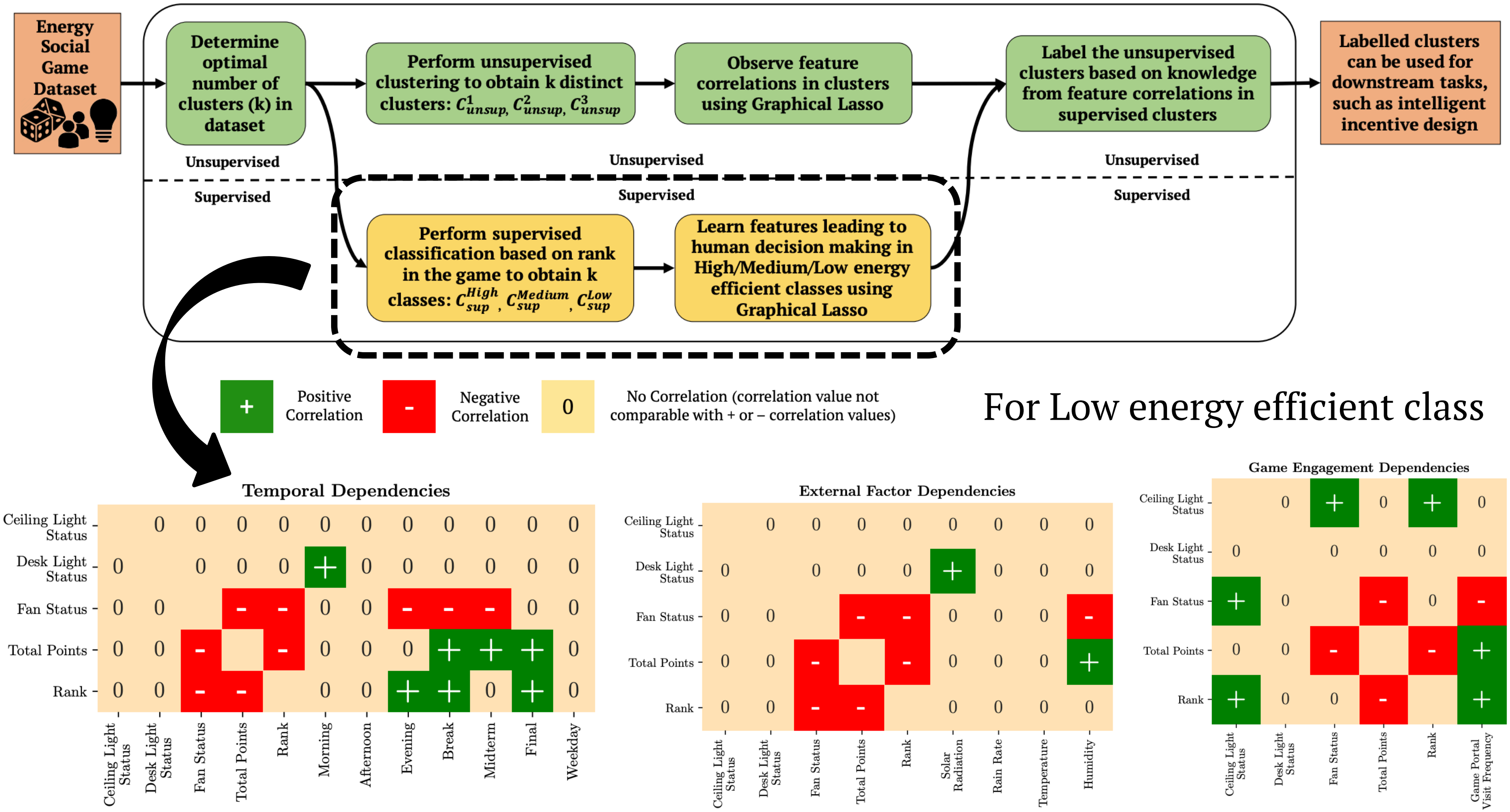
Social Game Dataset

Energy Social Game time-stamped data in per-minute resolution:

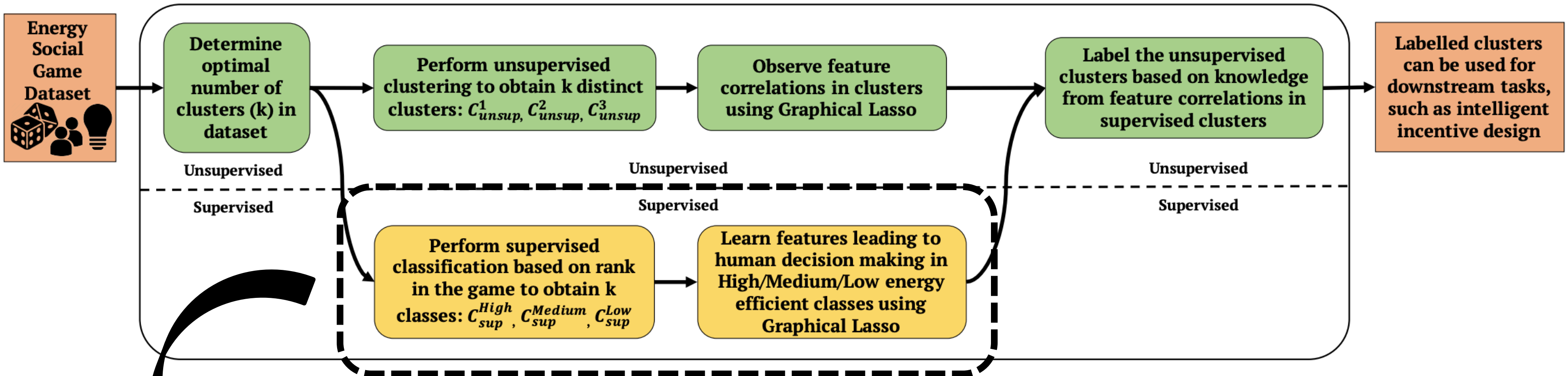
1. Resource (Ceiling/Desk Light, Fan, A/C) Status
2. Gathered points (from games and surveys)
3. Rank in the game
4. Frequency of visit to web portal
5. Weather metric such as humidity, temperature and solar radiation
6. Dummy features: Weekdays/Weekends/Midterms/Breaks/Finals

Ref: "Design, Benchmarking and Explainability Analysis of a Game-Theoretic Framework towards Energy Efficiency in Smart Infrastructure", I. C. Konstantakopoulos, H. P. Das, A. R. Barkan, S. He, T. Veeravalli, H. Liu, A. B. Manasawala, Y. Lin and C. J. Spanos, *arXiv preprint arXiv:1910.07899, 2019*

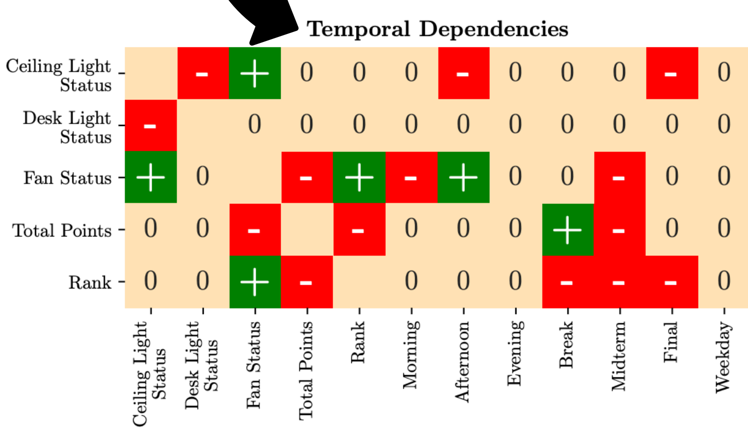
Feature Correlation Learning using Graphical Lasso

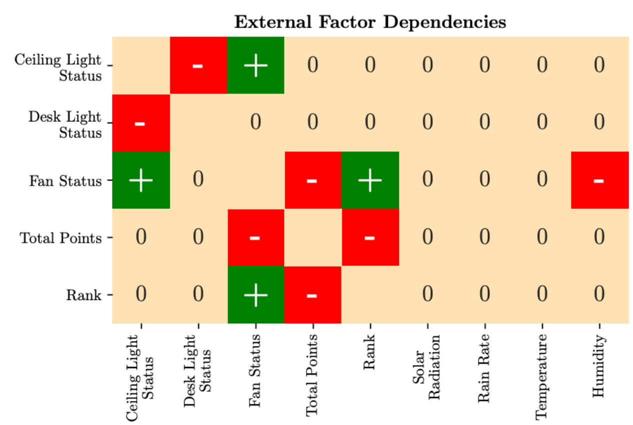


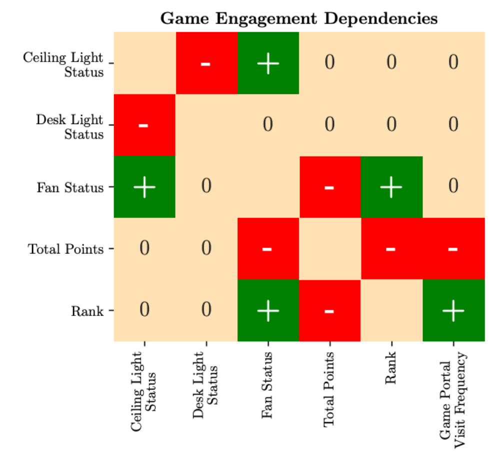
Feature Correlation Learning using Graphical Lasso



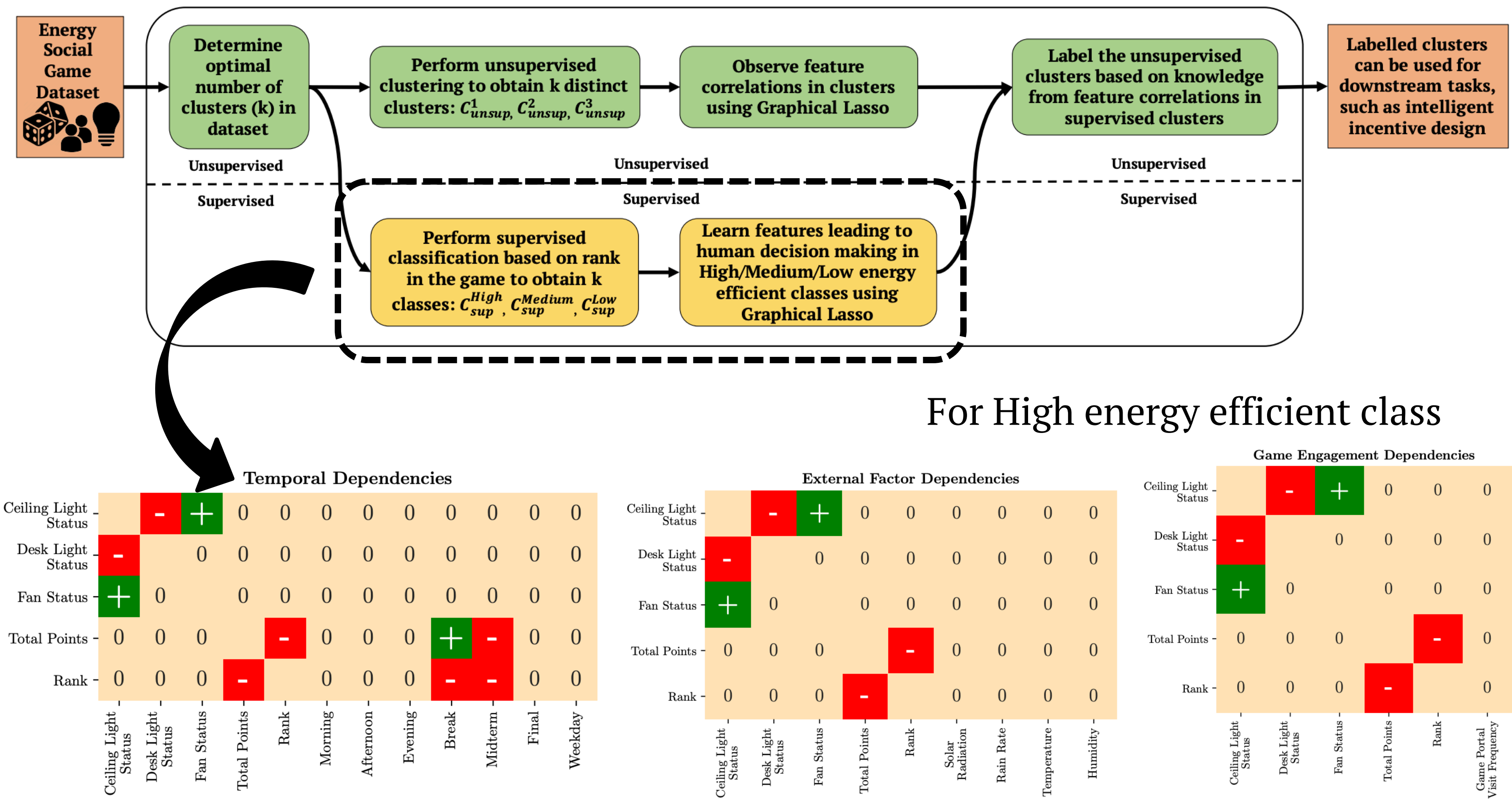
For Medium energy efficient class





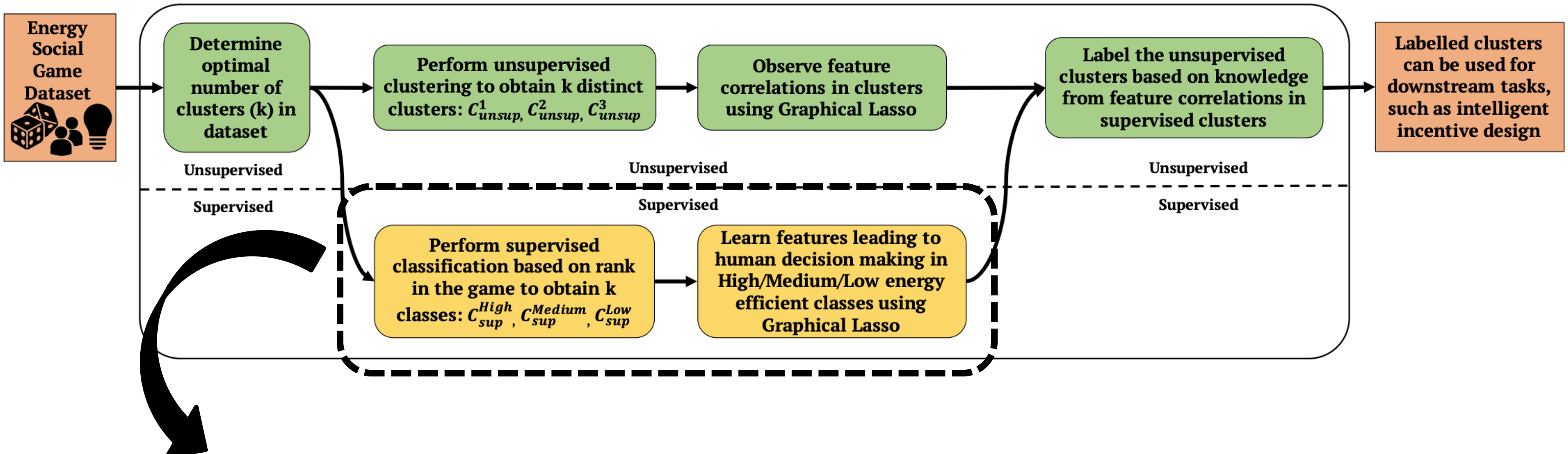


Feature Correlation Learning using Graphical Lasso



Causality Analysis using Grangers Causality

Enhances the explainability nature of our model

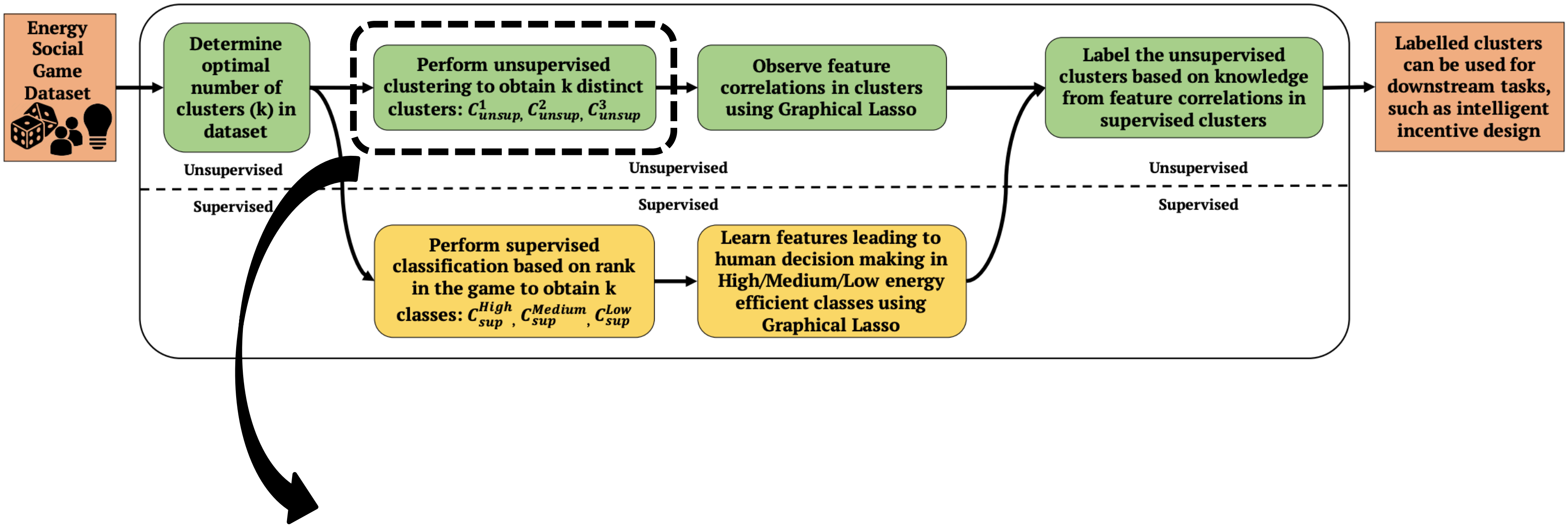


Test whether X causes Y	Fan $\Rightarrow$ Ceiling Light		Humidity $\Rightarrow$ Fan		Desk Light $\Rightarrow$ Fan		Ceiling Light $\Rightarrow$ Desk Light	
Player type	p-value	F-statistic	p-value	F-statistic	p-value	F-statistic	p-value	F-statistic
Low Energy Efficient	0.54	0.37	**0.004**	8.12	0.06	3.55	0.81	0.06
Medium Energy Efficient	**0**	21.2	**0.008**	7.06	**0**	113.6	**0**	25.8
High Energy Efficient	**0**	21.9	0.12	2.36	0.99	0.003	0.93	0.007

Under null-hypothesis, X does not cause Y

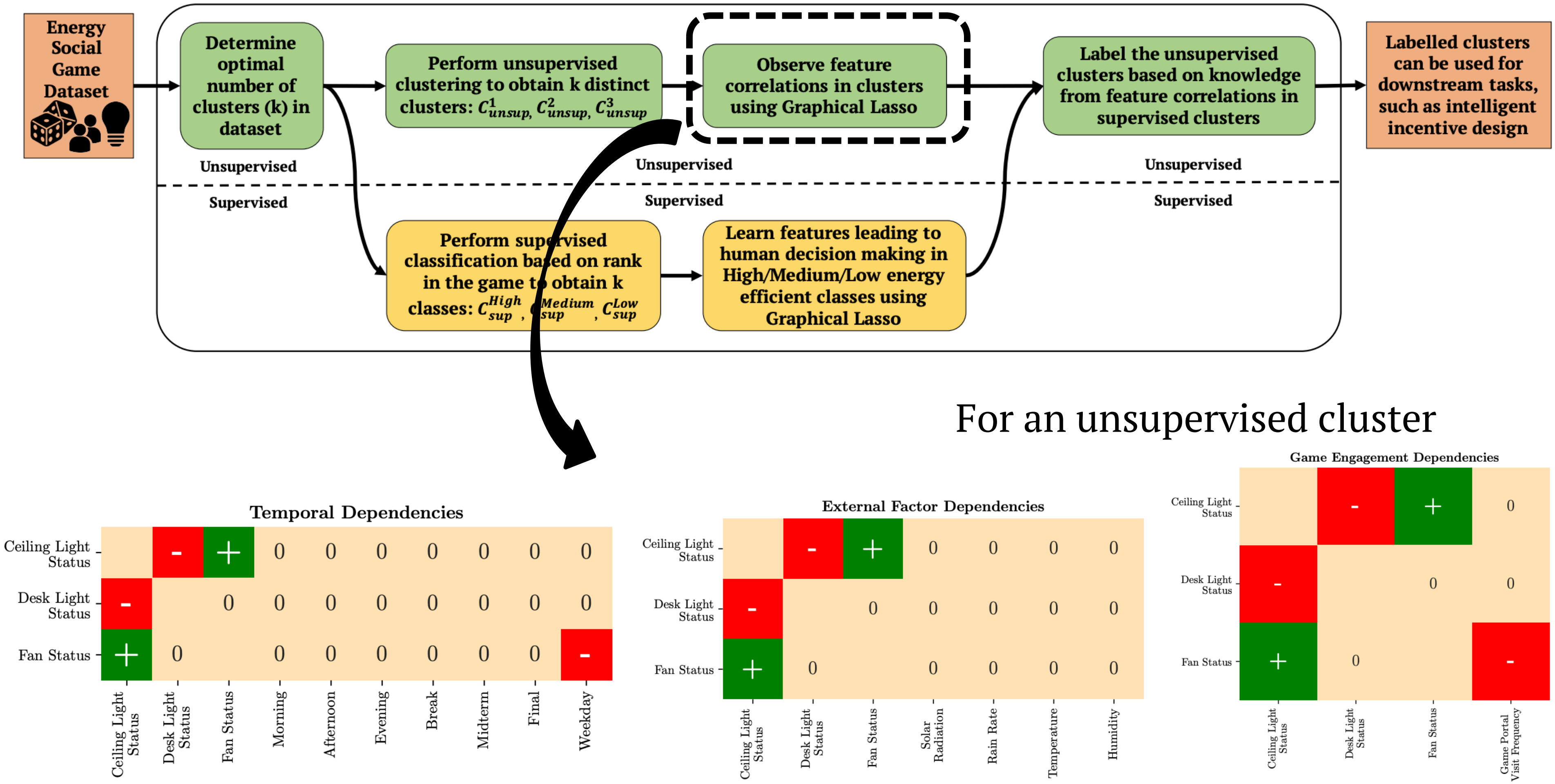
Afternoon $\Rightarrow$ Fan		Evening $\Rightarrow$ Ceiling Light	
p-value	F-statistic	p-value	F-statistic
0.01	6.1	**0**	25.3
0.46	0.55	**0.0007**	11.5
0.04	4.2	0.52	0.41

Unsupervised Clustering

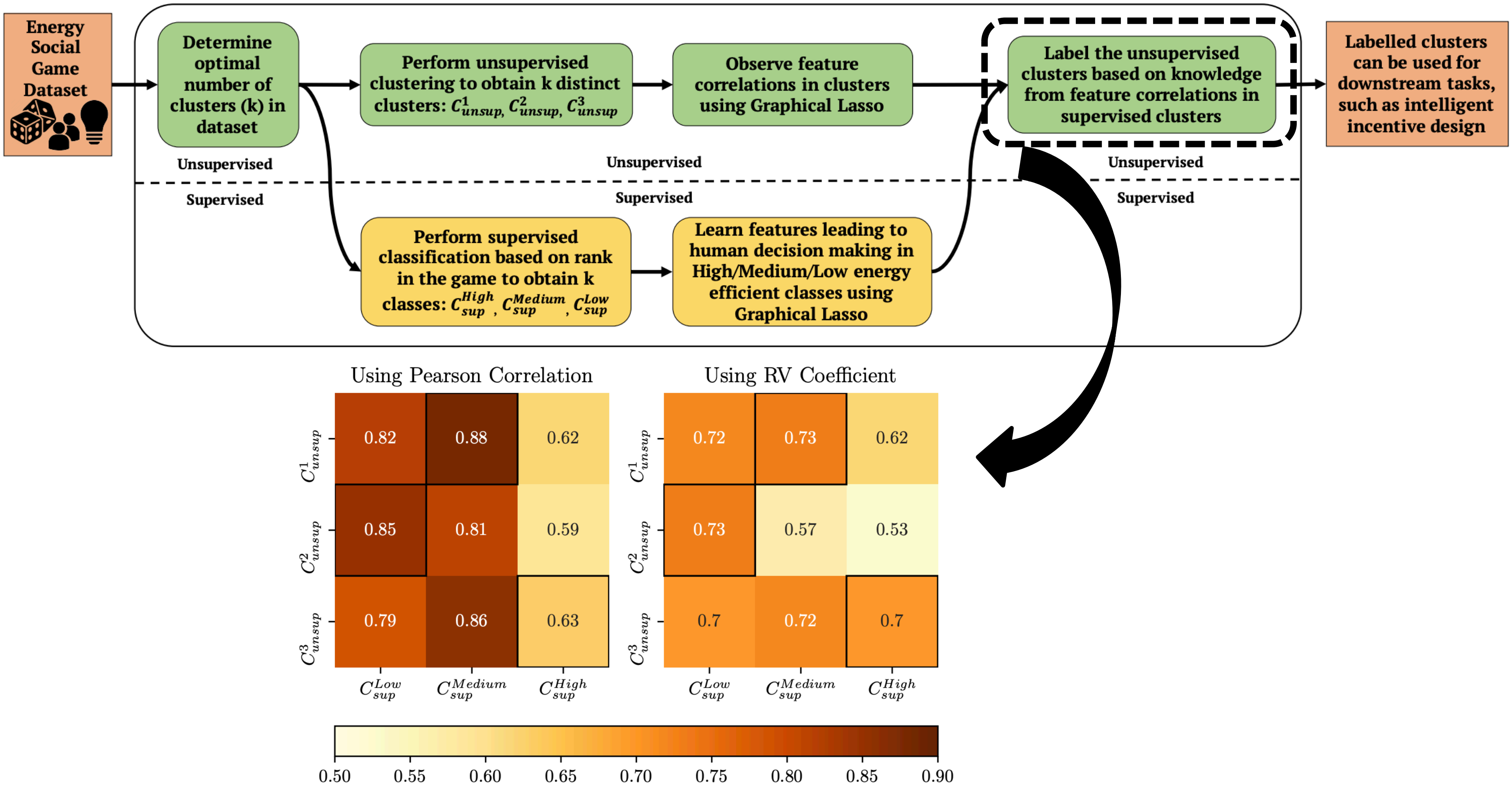


Principal Component Analysis (PCA) followed by minibatch K-means

Feature Correlation Learning using Graphical Lasso



Feature Correlation Learning using Graphical Lasso



Using Pearson Correlation

	C^{Low}_{sup}	C^{Medium}_{sup}	C^{High}_{sup}
C^1_{unsup}	0.82	0.88	0.62
C^2_{unsup}	0.85	0.81	0.59
C^3_{unsup}	0.79	0.86	0.63

Using RV Coefficient

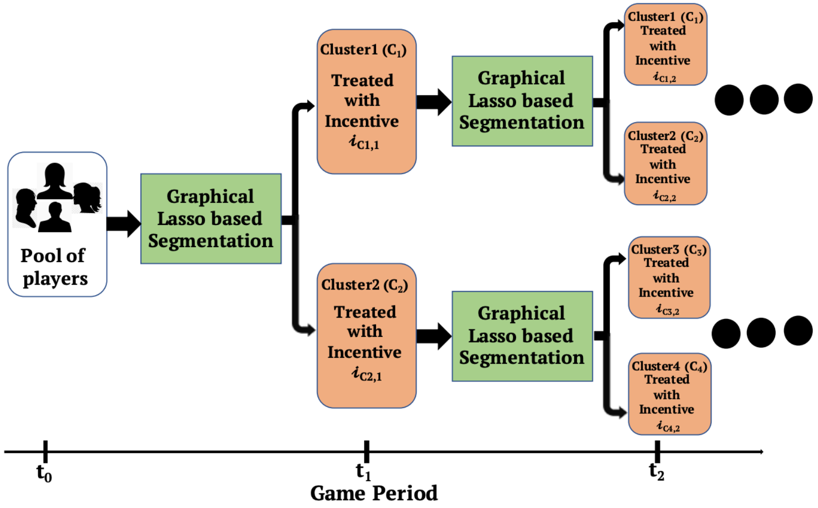
	C^{Low}_{sup}	C^{Medium}_{sup}	C^{High}_{sup}
C^1_{unsup}	0.72	0.73	0.62
C^2_{unsup}	0.73	0.57	0.53
C^3_{unsup}	0.7	0.72	0.7

Conclusions and Future Work

- A framework for segmentation analysis in energy game-theoretic frameworks
- Clustering of agent behaviors and an explainable statistical model
- Characterization of causal relationship among several contributed features explaining decision-making patterns in agent's actions.
- Specific incentives can be designed for characteristic clusters

Future Work

- Tree based Incentive Design
- Study of long term effects of social game with improved incentive design



Thank You!

Questions?

References

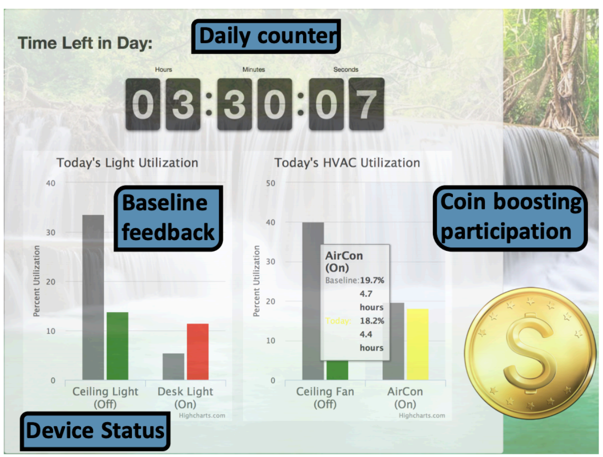
- “Design, Benchmarking and Explainability Analysis of a Game-Theoretic Framework towards Energy Efficiency in Smart Infrastructure”, Ioannis C. Konstantakopoulos, Hari Prasanna Das, Andrew R. Barkan, Shiying He, Tanya Veeravalli, Huihan Liu, Aummul Baneen Manasawala, Yu-Wen Lin and Costas J. Spanos, *arXiv preprint arXiv:1910.07899, 2019*

- “A Novel Graphical Lasso based approach towards Segmentation Analysis in Energy Game-Theoretic Frameworks”, Hari Prasanna Das, Ioannis C. Konstantakopoulos, Aummul Baneen Manasawala, Tanya Veeravalli, Huihan Liu and Costas J. Spanos, *arXiv preprint arXiv:1910.02217, 2019*

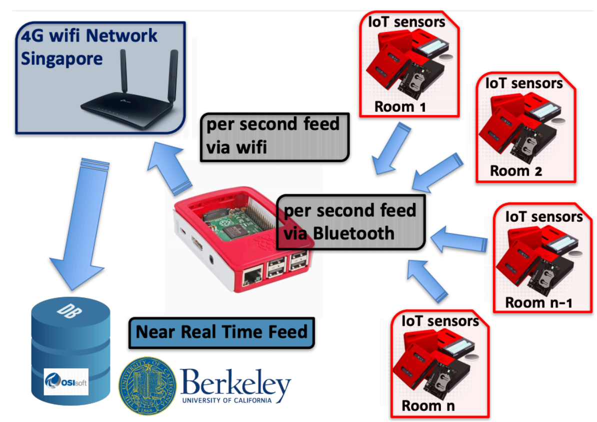
- Trevor Hastie, Robert Tibshirani, and Martin Wainwright. Statistical Learning with Sparsity: The Lasso and Generalizations. Chapman & Hall/CRC, 2015

Energy Social Game Experiment

- Experimental environment: Residential housing single room apartments in Nanyang Technological University (NTU), Singapore campus.
- Deployed IoT sensors for energy resource observation and employed an web-interface for interaction with players
- Energy usage observed: Ceiling Light, Desk Light, A/C and Fan
- Occupants were rewarded with points based on how energy efficient their daily usage is in comparison to their past usage and usage of other players in the game.



(a) Graphical user interface (GUI)



(b) Social game dataflow architecture design